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Performance of Multi Junction Photovoltaic Cells with High Concentration Ratio

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Abstract

Concentrating solar radiation on Photovoltaic (PV) has the potential to replace the expensive PV material with cheaper optical elements which also enhance the overall electrical output. The use of high solar concentration ratios with the triple junction III-V solar cells offers potential of high solar cell efficiency and power output. However, using high concentration ratios will increase the solar cell surface temperature which is inversely proportional to the PV electrical efficiency. This work investigates the effect of active cooling on the performance of triple junction PV cells with high solar concentration (up to 500X) in the harsh environment of Saudi Arabia where ambient temperatures can reach to 50^o C in summer time, but with good clearance index of 0.6 and high yearly solar radiation of up to 2200 kWh/m^2. Simulation results showed that as the concentration ratio increases, the effect of cooling on the PV efficiency increases.

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Keyword: triple junction solar cell; active cooling; passive cooling; high concentration; conjugate heat transfer; thermal modelling

1. Introduction

Solar PV power has been one of the fastest growing renewable energy technologies and it is anticipated that this technology will play a major role in the future of global electricity generation [1]. Saudi Arabia has high average yearly global solar radiation of 2200 kWh/m^2 [2], particularly Jubail industrial city (JIC) located at latitude 27.00^{o}N and longitude 49.66^{o}E with yearly average total daily solar radiation on a horizontal surface of 5987 Wh/m^2 (yearly average day hourly solar radiation is X=500 W/m^2) and clearance index of 0.62 [3]. The use of high solar concentration with the triple junction III-V solar cells offers potential of high solar cell efficiency and power output. Such use will cause high and non-uniform PV cell surface temperature which reduces the efficiency and power output from the cell and ultimately

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degrades its life [4]. There are only a few thermal analysis studies on single concentrator solar cell and most of these studies are focusing on passive cooling where thermal resistance, area of the heat sink, and thermal conductivity were analysed. Theristis et al concluded from their high concentration study that passive cooling is not dissipating enough heat from the cell even when a very large heat sink is used especially in high ambient temperatures [5]. Active cooling is more efficient in reducing the PV surface temperature and economically more feasible as removed heat by the cooling fluid can be utilised in different thermal applications [6]. This work investigates the effect of active cooling on the performance of triple junction PV cells with high solar concentration (up to 500X) in the harsh environment of Saudi Arabia where ambient temperature can reach to 50^{o} C in summer time using COMSOL multiphysics CFD software. Optical ray tracing technique was used to predict the solar distribution at the receiver plane of the optical concentrators which is the input to the PV cell surface using concentration ratios of 120, 250 and 500 respectively. Figure 1 shows solar distribution at the concentrator receiver plane for a concentration ratio of 500. Under such concentrated solar radiation, the prediction of the PV cell surface temperature and its efficiency will be of paramount importance; therefore, thermal simulation was carried out to investigate the effect of cooling

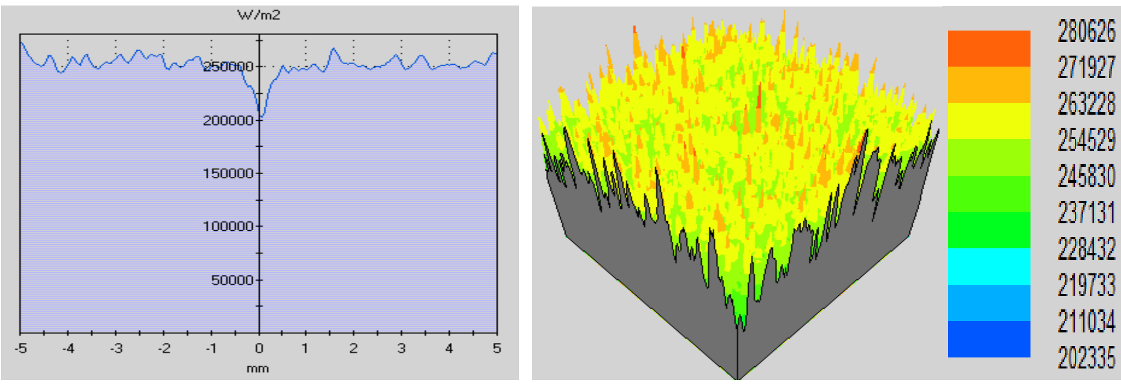
2. Thermal Modelling

Thermal modelling of C1M1 type PV cell with III-V multi-junction made of GaInP-GaInAs-Ge and area of $1cm^2$ to predict its temperature distribution was carried out using COMSOL multiphysics software. To investigate the effect of cooling on PV performance, the cell was placed above a cooling channel with hydraulic diameter of $6.67x10^{-3}$ m where water flows at a velocity ranging from 0.01 to 1m/s corresponding to Reynolds number of 73 to 7300. The solar radiation energy received by the PV cell is partially used to generate electricity and the rest is converted to heat. Kerzmann and Schaefer method was used to calculate the amount of input energy that is converted to heat (q_{heat}) as per equation 1 [7]:

$$q_{heat} = q_{rad}.(1-\eta_{pv}).CR \quad (1)$$

where q_{rad} is solar radiation incident on the surface of the PV cell, CR is the concentration ratio, and η_{PV} is the cell average electrical efficiency given as a function of thermal coefficient ($\beta_{thermal}$) at each concentration, efficiency at reference temperature (37%), and average PV surface temperature (T_{PV}) as shown in equation 2:

$$\eta_{PV} = 37\% -[\beta_{thermal}(T_{PV}-298.15)] \quad (2)$$



(a) (b)

Fig. 1. Concentrated solar radiation received by the PV cell (a) at centre line and (b) over the surface

This converted heat is transferred through the PV cell solid layers by conduction to the water channel where it was dissipated using forced convection. Also, some of this heat is radiated back from the cell to the ambient. Conjugate heat transfer physical model in COMSOL was used to solve the heat conduction and convection simultaneously. Figure 2 shows the temperature distribution through the centre plain of the PV cell assembly including the cooling channel at the average of the solar input shown in figure 1 and cooling water flow velocity of 0.2m/s. It is clear from this figure that as the water flows in the cooling channel, its temperature increases reducing its cooling effect and causing the PV cell surface temperature at the top right end to be higher. Figure 3 shows the PV cell surface temperature variation at different solar concentration ratios (120, 250 and 500) and cooling water velocity ranging from 0.1 to 1m/s. It shows that as the concentration ratio increases the temperature gradient along the PV cell increases, but as the water velocity increases, this temperature gradient decreases. For example at CR of 500, the PV surface temperature gradient is 10K at water velocity of 0.1 m/s and decreases to 5K at water velocity of 1 m/s. Figure 4 shows the effect of water velocity on the electrical efficiency of the PV cell at the given concentration ratios. It is clear from this figure that concentration ratio of 250 produces the highest electrical efficiency compared to CR of 120 and 500. However, at higher concentration ratio (500X), the overall efficiency drops due to the higher surface temperatures, therefore cooling becomes more effective in improving the PV cell efficiency which increases from 33.98% to 35.03% by increasing the water velocity from 0.01 m/s to 1 m/s. The simulation model was validated by comparing the manufacturer measured electrical efficiencies at different concentration ratios and temperature with the calculated ones. At the same temperature, one value for each concentration ratio (120,250,500) was compared as per the following: 34.20%, 34.59%, 34.89% are in close agreement with the manufacturer measured efficiency 34.50%, 34.50%, 34.90%.

3. Conclusions

Concentrating solar radiation on PV cells has the potential of reducing the number of PV cells used. Multi-junction solar cells can benefit from such high levels of solar radiation but suffer from the effect of high surface temperature. Cooling has a significant effect on concentrated multi-junction solar cells efficiency and becomes more effective at higher concentrations. Thermal simulation of concentrated multi-junction solar cells is an effective tool to predict temperature distribution through the PV which enables applying the appropriate cooling levels to improve the PV efficiency under given concentration.

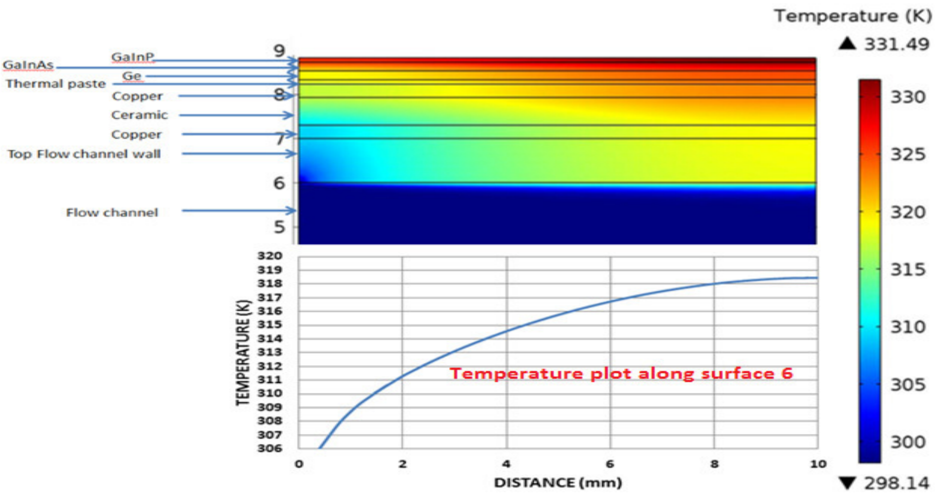


Fig. 2. Temperature distribution on Multi-junction PV layers (at U=0.2 and CR 500).

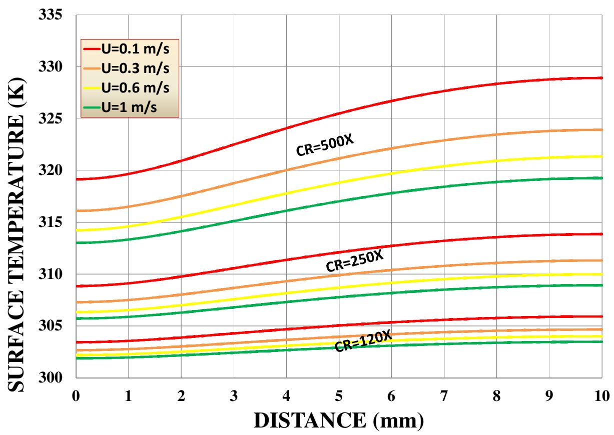


Fig. 3. Temperature variation along the PV surface.

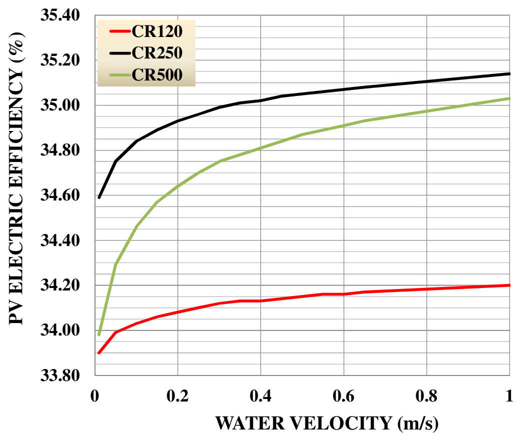


Fig. 4. Effect of water velocity on PV electric efficiency with three different concentration ratios (CR= 120, 250 and 500)

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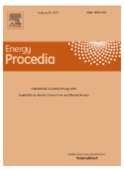

Biography

Abdulrahman Aldossary is a PhD research student in the solar energy research group at the University of Birmingham. He graduated with MSc in Mechanical Engineering from the University of Manchester in 2010.